ADAPTIVE BEAMFORMING FOR SUBMARINE-SATELLITE COMMUNICATIONS WITH THE (MBCA) MULTIELEMENT BUOYANT CABLE ARRAY ANTENNA

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ABSTRACT

In order to provide the capability for submarines to communicate through a satellite while remaining submerged and traveling at operational speeds a towed buoyant cable array antenna is being developed. The array is adaptive from the point of view that the direction of the satellite need not be known, the position and orientation of the array need not be know, and the shape of the flexible array need not be known. A blind equalization procedure is used to estimate the signal space from the downlink signal and create a spatial matched filter for receive. While the frequency division satellite system is intended to allow only one signal per frequency slot, the system can also operate in the presence of jamming by separating multiple sources spatially.

Once the downlink receive antenna weights have been obtained, the more difficult task of obtaining uplink weights at a separated frequency must be performed. Since no data is available for blind equalization at the transmit frequency a frequency extrapolation method is used to extend the downlink receive weights to frequencies beyond where the equalization data was collected. This extrapolation is complicated by 2-pi ambiguities of the measured phases as well as amplification of measurement errors in the extrapolation process. An algorithm has been developed that performs well

1. INTRODUCTION

An adaptive array antenna is being developed to provide the capability for submarines to communicate through a satellite while remaining submerged and traveling at operational speeds[1]. The antenna consists of 12 elements in a linear floating hose that is attached at the end of a long tow cable. The flexible antenna rides the waves so the instantaneous shape and orientation of the array are unknown. The multiple elements provide margin to the communication link budget through the increased gain compared to a single element system, but the principle advantage of the multiple elements is the element diversity which provides resistance to element wash-over effects[2]. When one or several elements are washed over and incapable of receiving or transmitting the remainder of the array will carry the load with only a small fade rather than the deep dropout that would be experienced by a single element antenna.

In order to provide the antenna gain and stability from the multiple elements, the downlink, i.e., receive, signals are combined in an RF beamformer after being phase shifted with digitally controlled analog phase shifter. The only amplitude control is 1-bit, i.e. the channel can be turned on or off. This on/off switch allows an element to be turned off when its adaptive weight is very small and the use of the element at full gain would add more noise than signal. This results in only a modest loss relative to implementation of the actual optimum amplitude weight. The beamforming is done in the analog domain so that the whole adaptive array system can be used as a drop-in antenna for existing communication systems without impacting other aspects of the communications hardware or methods of operation. The weight determination for receive beamforming is based on sampling the downlink signal on the multiple elements to determine their phases and is covered in section 2.

When a signal is to be sent up to the satellite a different frequency is used, differing from the downlink frequency by about 15%. Since there is no signal from the satellite at the uplink frequency to sample, an alternative method of determining the transmit weights must be used. The method of transmit phase determination is based on calculating receive weight phases on two different downlink frequencies that are separated. The phase on each of the elements is then extrapolated linearly to the frequency where the transmit weights are to be used. Since the satellite is constantly transmitting on all downlink frequencies there is no problem finding two sets of separated adaptive weights for the extrapolation process. Transmit beamforming with frequency extrapolation is covered in section 3.

2. RECEIVE BEAMFORMING

2.1 Algorithm and Estimation Accuracy

The main goal of making the system adaptive is to phase shift the element signals so that their phasors are aligned tip-to-tail to create the largest possible resultant and therefore high gain. This is accomplished by receiving and sampling the downlink signal from the satellite on each of the elements and creating a sample covariance matrix. The satellite system that this antenna system works with is frequency channelized so there should be only one signal, i.e., the signal of interest, passed through the receivers

The overall change in power levels over the 40 second run is caused by the changing range of the source on the helicopter as it flew past from stern to bow. The output of the RF beamformer was also received and sampled and is show as the top curve of Fig. 3. It is clear that the seven elements provided both gain and signal stability. Dropouts on individual channels show up in the beamformed signal as small dips on a signal that has much higher *SNR* due to the array gain.
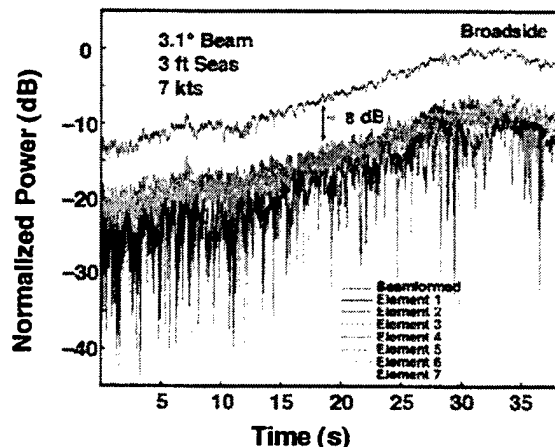

Figure 3. The element power vs. time is plotted for a helicopter fly-by experiment. The beamformer output is the top curve.

The individual elements are spaced far enough apart so that the waves impact them in an independent fashion. If the elements are too close, a washout on one element would be highly correlated with washouts on the neighboring elements and many more elements would be need in the array to reach the performance achieved with the widely separated element. Since there is a desire to make the array as short as possible with few element for simplicity, an interesting tradeoff arises for the array design of the spacing and number of elements required to meet the performance goals [3][4].

2.3 Weight Smoothing

In addition to providing gain and signal level stability, it is also necessary to be sure that the phase at the output of the beamformer is stable so that the signal modulation is not corrupted. While this is not a beamforming task in itself, it is necessary for any modulation system that depends on the signal phase. The beamformer output phase is arbitrarily set at every weight update cycle by the adaptive weights which are only determined within a random phase factor. Both the old weights and the new will provide good beamforming at the transition time, but there will be a phase jump at the beamformer output unless corrective action is taken. In this adaptive system a correction phase is determined for the new weights by applying both sets of weights digitally to the new block of data and calculating the average phase shift between the output of the old weights relative to the new weights. This measured phase offset is then used as an adjustment on the new weights before they are applied to the RF beamformer.

2.4 Interference

While it is intended that the system operate with only one signal present during the estimation of the covariance matrix, it is possible that a jammer from a direction other than the direction of the satellite would try to confuse the adaptive process. If a large jammer signal is present along with the smaller desired signal, the covariance matrix will have two large eigenvalues rather than one. The two eigenvectors associated with the two large eigenvalues span the signal space of the two signal vectors. To a large extent a one-to-one association can be made between each eigenvector and one of the signals if the power of the two signals is different, although strictly speaking each eigenvector will have a portion of each signal if the signals are not spatially orthogonal. With a larger jammer, the signal vector can be estimated by the second eigenvalue and eigenvector. If the conjugated of this second eigenvector is used as the array weight vector then the desired signal will be well received and the jammer will be well rejected since the eigenvectors are orthogonal to each other.

The degree of separation of the signals into separate eigenvectors can be seen by looking at the inner product of the second eigenvector with each of the two signal vectors. The difference between the two represents the null depth that is achievable. The degree of separation, i.e., the null depth, for spatially separated signals can be represented by:

$$ND = \frac{\left(\dfrac{P_1}{P_2}\right)^2}{N},$$

where P_n is the signal power and N is the number of element in the system. This is illustrated in Fig. 4 for a 10-element system where simulation results are plotted at each integer dB level of signal power separations. For most levels of signal power separations nulling and signal reception can be achieved.

This has been confirmed in seatrials with digital beamforming on the seven element system where a jammer signal was placed on the tow boat while the weaker desired signal was transmitted from a helicopter. The jammer to signal level was 16 dB on the elements so 40 dB null depth was predicted. By using the second eigenvector, the array signal-to-interference-ratio was improved by 45 dB relative to the single element signal-to-interference-ratio.

Jamming and interference are not expected in the current application, but if they are expected, these results show that enough signal separation can be achieved to improve the beamformer output. If nulling is desired it is expected that digital beamforming and amplitude control would be required for better accuracy unlike in the current application.

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The problem of measurement noise amplification in the extrapolation process can be thought of as arising from the derivative in the Taylor series, since is well know that differentiating noise will amplify errors. If an assumption is made that the RMS measurement phase noise is the same at each of the two downlink receive frequencies an expression for the phase error amplification factor can be given by

$$A = \sqrt{1 - 2M + 2M^2}.$$

This says that if the RMS phase error at the two downlink receive frequencies is σ, then the RMS phase error after using an extrapolation ratio of M is $A\sigma$ at the uplink transmit frequency. The amplification factor, A, is always greater than 1.0 and is approximately linear for Ms ranging from one to five. A plot of the amplification factor is shown in Fig. 5. It can be seen that if a certain phase error level is required on transmit in order to minimize the beamforming loss then the phase error requirement on the receive weights is five times tighter for an extrapolation ratio of 4.0.
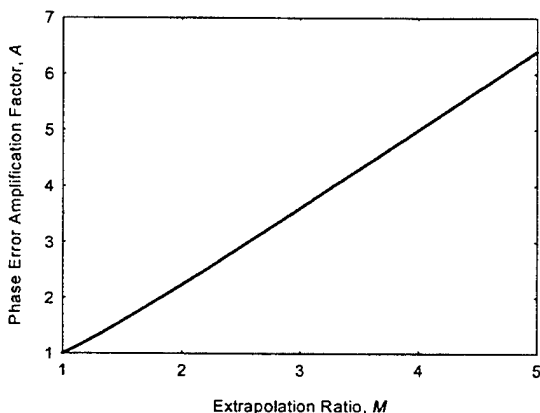
Figure 5. The phase error amplification factor, A, is approximately a linear function of extrapolation ratio, M, for values of M ranging from one to five.

It can be calculated and it is shown in Fig. 1 that if the transmit beamformer loss is to be limited to about 1.0 dB, then the RMS transmit phase error must be limited to about 0.5 radians (28 deg.). The plot in Fig. 6 shows the limit of RMS receive phase errors that must be obtained in order to achieve the required 0.5 radians at the transmit frequency after extrapolating. It can be seen that transmit beamforming becomes quite difficult for large extrapolation ratios.
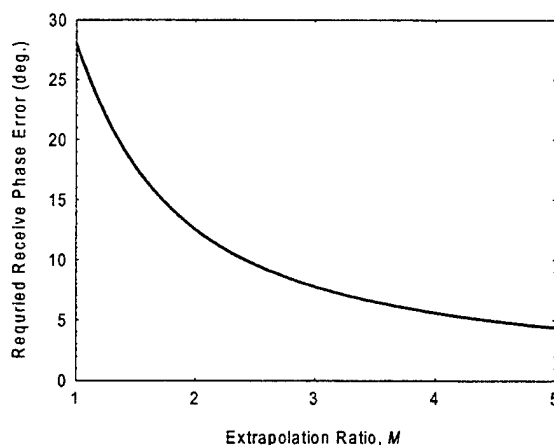
Figure 6. The RMS receive phase error that is required in order to achieve 1 dB of transmit beamforming loss is plotted as a function of the extrapolation ratio, M.

3.4 Experimental Results

A field experiment has been conducted to prove the concept of transmit extrapolation beamforming using the receive-only test array described earlier in Sec. 2. Modifications were made to the system to accommodate the transmit demonstration through a receive-only test system by using reciprocity. Four elements were used. Signals were transmitted from the helicopter at three frequencies, representing the two downlink frequencies and the one uplink frequency. Adaptive weights were calculated using the receive algorithm at all three frequencies. The two sets of weights at the downlink frequencies were then extrapolated to estimate weights for the transmit frequency. These extrapolated "transmit" weights were then compared to the receive adaptive weights that were calculated directly at the transmit frequency by performing digital beamforming with the two sets of "transmit" weights. The results are plotted in Fig. 7 along with the powers of each of the four individual channels for a case with an extrapolation ratio of 2.0. It is clear that both sets of transmit weights perform well with only a small loss using the extrapolated weights relative to the directly calculated (non-extrapolated) weights.

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